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Experimental investigations on diesel engine performance and emissions using biodiesel adding with carbon coated aluminum nanoparticles

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Abstract

This study investigates the effects on engine performance and exhaust emissions using carbon coated aluminium (Al@C) nanoparticles as additives in palm oil methyl ester biodiesel. The nanoparticles were blended with the biodiesel fuel in the mass fractions of 30 ppm under ultrasonic mixing. A series of experimental tests have been conducted using a heavy-duty diesel engine test bench provided by Cummins. The influences of three kinds of biofuel, including biodiesel, biodiesel with ethanol, and biodiesel with ethanol and nanoparticles, have been studied in detail. The results show clearly that adding Al@C nanoparticles can reduce brake specific fuel consumption (BSFC) remarkably with average of 10%. NOx and CO emission reduce significantly in nanoparticles fuel blends cases at about 12% and 9% respectively, comparing with neat biodiesel. However, total hydrocarbon compounds (THC) emission and emitted particle numbers increase with adding nanoparticles.

Keywords: biodiesel; carbon coated aluminum nanoparticles ; engine performance; pollutants emission

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1. Introduction

Confronted with severe pressure and challenges under the framework of development in vehicle manufactory and demand of energy consumption and environment, study on improving efficiency of energy use and reducing pollutant emissions have drawn more and more focuses from the last decades. There are three normal methods of reducing pollutant emissions: engine modification, developing renewable alternative fuels, and improving exhaust gas treatment [1]. A growing body of research recognizes the importance of biofuels in reducing pollutant emissions with no or minor impact on engine performance. In recent years, many researches reveal that adding nanoparticles as nano-catalysts or nano-additives in biodiesel-diesel blend can improve the engine performance, combustion efficiency and reduce exhaust emission. The most common nanoparticles used are ceramics and metal oxides, such as alumina [1-3], zinc oxide [4, 5], titanium oxide [6], cerium oxide and cerium oxide with ferrocene [7-9], carbon nanotubes [10] and cerium oxide nanoparticles and carbon nanotubes as fuel-borne additives [11]. However, few study focus on the influence of nanoparticles with core-shell structure, such as carbon coated metal nanoparticles as a novel additive, which has high thermal conductivity and better lipophilicity than metal oxide because of carbon outer layer [12]. Therefore, it is necessary to understand the effect of adding carbon coated metal nanoparticles with biodiesel blend on engine performance and exhaust emission.

2. Experimental method

Biodiesel with various concentration of palm oil methyl ester (0, 10, 20, and 50 % respectively) were selected as base fuels. As nanoparticles tend to disperse homogenously in ethanol, a small certain amount of carbon coated aluminum (Al@C) nanoparticles at a dosage of 30ppm in mass fraction was dispersed in ethanol solution using ultrasonic bath for 30 mins first. Then the obtained ethanol suspension was mixed with biodiesel under ultrasonic treatment for another 15 minutes at volume ratio of 4:96. The morphology of Al@C nanoparticles was examined by Transmission electron microscopy (TEM, JEOL JEM-2010HR).

The engine test methods included engine performance system, exhaust gas analysis system and filter rig. These could record combustion performance, emissions concentrations and the results of burned particles from their own data acquisition system. A heavy-duty diesel engine (ISBe5, Cummins) was used to investigate the effect of target fuel blends. A common rail fuel injection system, which had a maximum value of 1800 bar pressure and has four solenoid injectors for each cylinder, as shown in Figure 1. The experiments were undertaken in a four-cylinder in line, four-stroke with displacement of 4.5 liters to produce higher power and torque in Euro 5 emission standard. Engine performance was detected by a combustion analysis system – produced by National Instrument, with data acquired from LabVIEW and MATLAB programs. The other parameters of working conditions were controlled by DaTAQ console. Subsequently, emissions characteristics, such as nitrogen oxide (NOx) emission, total hydrocarbon compounds (THC) and carbon monoxide (CO) emission, were recorded by Horiba MEXA 1600D. The value of emission particle numbers was measured by Horiba MEXA SPCS 1000 in real-time as well.

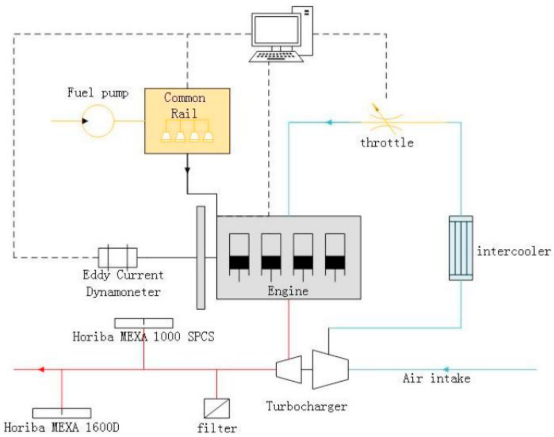


Fig. 1. Schematic diagram of engine test bench

3. Results and discussion

The morphology of carbon coated aluminum nanoparticles exhibit the core-shell structure clearly, as shown in Fig. 2. The core-shell structure particles are quasi-spherical with diameter ranging from 60 nm to 120 nm. The disordered outer layer with thickness around 5 nm in Fig. 2(b) indicates amorphous structure of graphite. It also displays that the core is crystalline, having a calculated lattice spacing of 0.236 nm, which consistent with the interlayer spacing corresponding the (111) plane of face-centered cubic aluminum (JCPDS: 89-4037). The TEM and high-resolution TEM image reveal that the aluminum cores are completely surrounded by carbon shells. Core-shell structure of the nanoparticles with metallic core and carbon shell could improve suspension stability of the nanoparticles dispersed fuel, as metal tends be hydrophilic.

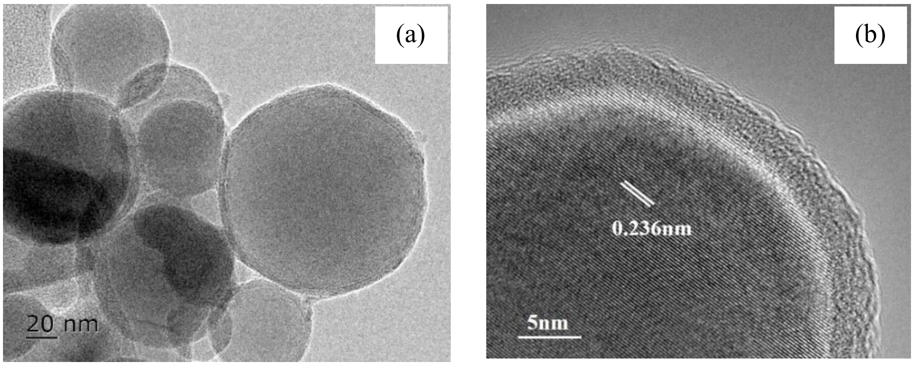
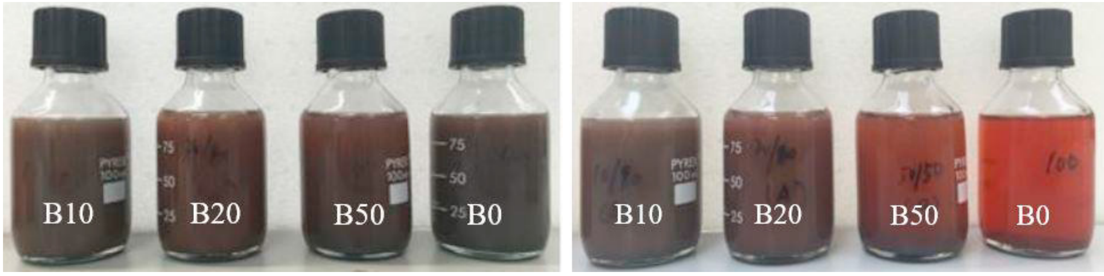


Fig. 2. (a) TEM image; (b) HR-TEM image of Al@C nanoparticles

The sedimentation photographs of as prepared biodiesel blend adding with Al@C nanoparticles before and after quiescence for 15 days are exhibited in Fig. 3. Four kinds of biodiesel with different palm oil methyl ester concentration are labeled as B0, B10, B20 and B50 for 0/100, 10/90, 20/80 and 50/50 respectively, corresponding to the ratio of palm oil methyl ester / diesel. Significantly, different agglomeration could be observed from four suspension biodiesel samples. No obvious sedimentation is found for B10 sample, and a little agglomeration is observed for B20 suspension, whereas B50 and B0 sample reveal obvious sedimentation and leading to the emergence of original reddish brown color from neat biodiesel. Furthermore, another 15 days later, B10 suspension sample still keep stable and homogeneous, indicating its relatively good dispersion stability under the preparation process described above. It is thereby that the fuel blends of 30 ppm Al@C nanoparticles with 4% ethanol added into 10% palm oil-biodiesel (B10E4N30) is selected as the most suitable feedstock for the following engine tests.



(a) (b)

Fig. 3. Digital photographs of biodiesel suspension employing Al@C nanoparticles with various ratio of palm oil methyl ester (a) Fresh prepared; (b) After quiescence for 15 days.

Three kinds of fuel blends have been used in the tests, including diesel with 10% palm oil methyl ester (B10), B10 biodiesel with 4% ethanol (B10E4) and B10E4N30, to compare the effect of Al@C nanoparticles on engine performance and emission characteristic. The tests on engine were repeated using the baseline fuel – diesel to ensure the engine test data (including the engine performance and emissions) recorded were reliable. As shown in Fig. 4 shows the fuel consumption of three different fuel blends. Each plateau represented one mode in European Stationary Cycle (ESC) test, and there are 12 modes in one ESC cycle. Clearly, the fuel consumption of B10E4N30 is lower than the other two samples in the whole cycle, except for the point 6. It is considered that the engine is working in the lowest speed with only 25% load at point 6. When the engine finish the point 5 (with 75% load), the fuel consumption goes high and keep in idle time. Then the engine began the point 6, the inertial effect of fuel system lead to higher fuel injection in the beginning of the point 6. However, no obvious difference is found for the fuel consumption of B10E4 and B10. There is a remarkable decrease in BSFC for B10E4N30 at the average of 10% in 12 modes under ESC condition, except point 6, comparing with other two fuel blends. The biggest decline of BSFC is about 15% at the point 11 for B10E4N30 compared with B10. However, only ethanol adding condition presents a slightly increase by only 0.3% (B10E4 vs B10). These results indicate clearly that Al@C nanoparticles play an important role in reducing the fuel consumption.

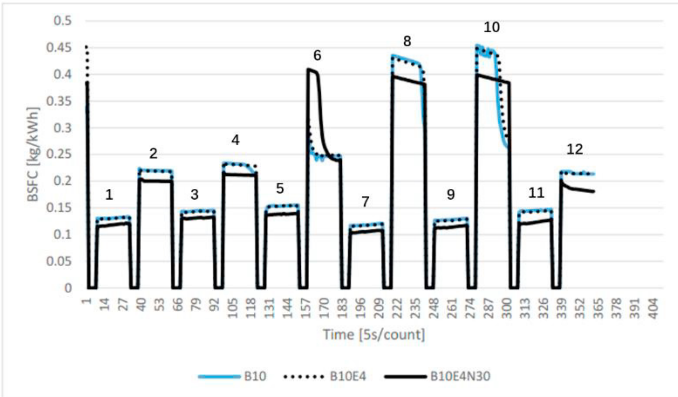


Fig. 4. Brake specific fuel consumption (BSFC) of using three kinds of fuel blends.

The test results of emission characteristics are displayed in Fig. 5. As can be seen from the graph in Fig. 5(a), in terms of nitrogen oxide emission, B10E4N30 is significantly less than the other two samples, while B10 and B10E4 exhibit almost the same except at 100% load. It is apparent that the specific emission of NOx decrease along with increasing engine loads, and the NOx emission markedly falls down in 1810 rpm with Al@C nanoparticles adding. The lowest value of NOx emission for B10E4N30 is 3.45 g/kWh at 100% load. It is obviously that adding Al@C nanoparticles result in the decline of NOx emission at 10 modes out of 12, which indicated that nano-additives have less effect in low load conditions, as shown in Fig. 5(b). The average value of NOx emission decline for B10E4N30 comparing with B10 is about 12%, of which the maximum decrease was at point 1, approximately by 26.5%. It is interesting to note that in all fuel blend samples of this study, adding Al@C nanoparticles is the main reason for NOx decline. By considering the weighting factors of 13-mode cycle, the value of the NOx decline on B10E4N30 compared with B10 and B10E4, is 9.9% and 8.8%, respectively. Almost the same results can be obtained from CO emission with the average reduction of around 9% comparing to B10. It is supposed that Al@C nanoparticles as an oxidation catalyst leads to higher carbon combustion activation and heat transfer rate, and hence promoting complete combustion that reduce the emission levels of NOx and CO. Hosseini [3] found as well that the large surface contact area of alumina nanoparticles raised the chemical reactivity, which consecutively shortened the ignition delay, and improved degree of fuel-air mixing and uniform burning leads to complete combustion.

Fig. 5 (c) shows the value of total hydrocarbon emission decrease with intensity of the equivalence ratio Ø rising at constant speed of 1810 rpm. It can be seen obviously that B10E4 has highest THC emission value, while B10 sample exhibit lowest than other two blend. A rise by over 50% on more than half modes can be found for B10E4N30, comparing with B10. These results may be because diesel engines could adjust its injection timing and ignition delay with the rise of fuel injected (equivalence ratio), leading to the decline of THC exhaust until the value of equivalence ratio even higher at 0.9. From the data collected in the exhaust line for particulates, particles emitted per unit kWh power output is used to analyse the particles number (PN) in constant speed, as shown in Fig. 5 (d). The amount of particulates for B10E4N30 is the highest throughout the period, rising from around $7.5X10^{10}$ #/kWh to just over $2X10^{11}$ #/kWh in full load condition. It is supposed that Al@C nanoparticles can not be burned totally during combustion process because of metal core, which resulting to a distinct increase of emitted particles numbers.

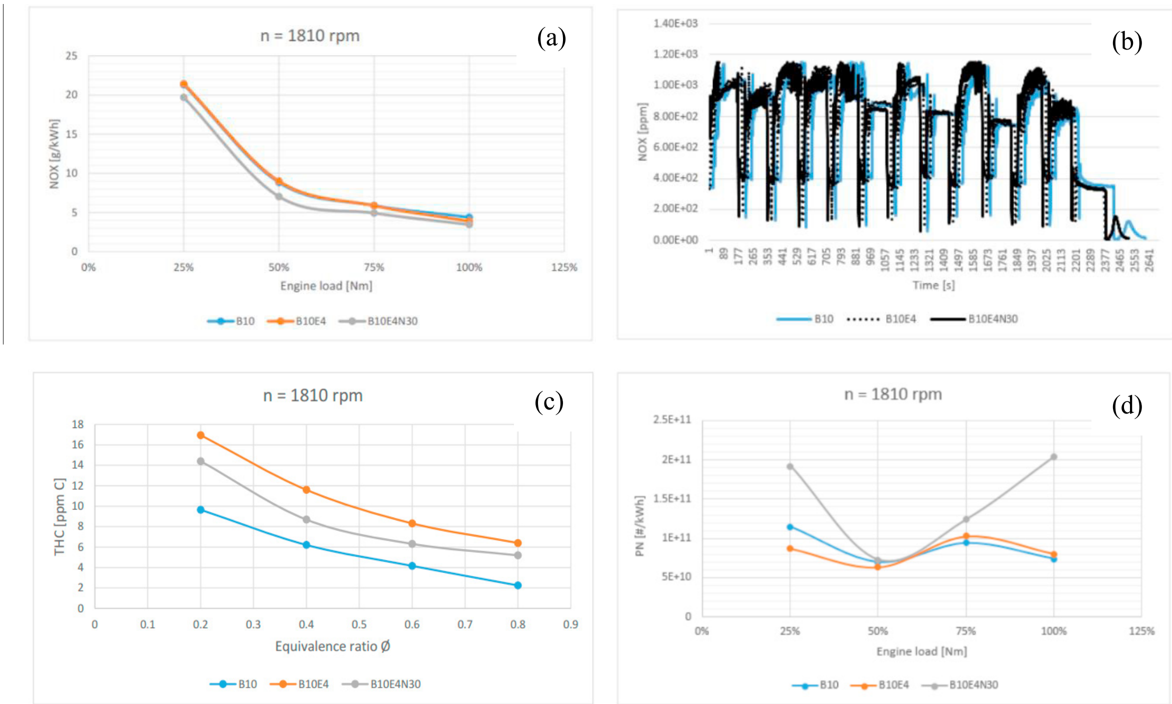


Fig. 5. Emission characteristics on three kinds of fuel blends

(a) Nitrogen oxide emission with various engine load in 1810 rpm; (b) Comparison of NOx emission in three fuel blends; (c) Variation of THC emission with equivalence ratio; (d) PN values with various engine load in 1810 rpm.

4. Conclusions

In summary, stable and homogeneous fuel blends of B10 palm oil methyl ester adding with Al@C nanoparticles has been prepared successfully. The engine performance and exhaust emission characteristics have been studied for biodiesel with and without Al@C nanoparticles and ethanol. Compare with pure biodiesel, using B10E4N30 can improve fuel economy by reducing the BSFC with average of 10%. Meanwhile, the reduction of NO_x and CO emission reach about 12% and 9% respectively. However, significantly increase on THC emission and emitted particles numbers can be found for B10E4N30, comparing with B10. Therefore, adding Al@C nanoparticles in biodiesel provide an effective approach to improve engine performance and reduce emission to some extent. Further study is to be carried out to investigate the mechanism of the combined effect of nanoparticles and ethanol on the engine performance.

Acknowledgements

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